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The Pacific Ocean subtropical cell surface limb

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Abstract. The subtropical cells (STCs) cycle subtropically subducted water to the equator, where it upwells and flows poleward at the surface, exchanging heat and freshwater with the atmosphere. Pacific STC surface flow is analyzed using drifter data. Mean surface velocities are estimated. The mean divergence reveals substantial equatorial upwelling. Off-equatorial downwelling around $\pm 4^{\circ}$ latitude suggests that about half the upwelled water may recirculate in shallow tropical cells. Pathways and time scales for the poleward surface limb of the STC are estimated. Mean streamlines reach $\pm 9^{\circ}$ latitude after half a year and $\pm 22^{\circ}$ after 2 years, taking a more convoluted path in the northern hemisphere. They reenter the subtropics in the western half of the basin, far from the subduction regions feeding the equatorward limbs of the STCs, reinforcing the point that the STCs are intrinsically linked with the global ocean circulation.

1. Introduction

A subtropical cell (STC) is the part of the ocean circulation that brings subtropically subducted water in the thermocline to the equator, upwells it there, and moves it back poleward at the surface [*Lu et al.*, 1998] where it affects the sea surface temperature (SST) and exchanges heat and freshwater with the atmosphere [*Neelin et al.*, 1998]. Model results suggest STCs play a potential role in modulating climate either by advecting subtropical water with varying temperature and/or salinity to the equator [*Gu and Philander*, 1997], or by varying the amount of subtropical water advected to the equator [*Kleeman et al.*, 1999]. These variations may in turn modulate processes such as ENSO that are associated with changes in equatorial SST. Of course the STCs are not the only candidates for decadal modulation of ENSO dynamics and predictability [*Kirtman and Schopf*, 1998]. In addition, the STCs are not closed cells, and therefore play a role in the global ocean circulation. For instance, in the Pacific Ocean, about 10×10^{6} m^{3} s^{-1} of water from the southern hemisphere must cross the equator to feed the Indonesian throughflow [*Gordon et al.*, 1999]. This water cycles through the Pacific STC on its way north [*Wijffels*, 1993].

Of the three oceans, the Pacific STC is perhaps the best defined. Observational analysis documents its mean subsurface pathways [*Johnson and McPhaden*, 1999]. However, the surface limb where water upwelled on the equator flows poleward owing to the Ekman drift is not well described. This manuscript presents an observational analysis of the Pacific STC surface limb. The sections that follow describe the data and their processing, the mean surface velocity field, the surface divergence, the surface pathways and time scales, and the potential connection of the Pacific STC surface limb to the global ocean circulation.

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2. Data

Global Drifter Program positions and velocities interpolated to 6-hourly intervals by kriging [*Hansen and Poulain*, 1996] were obtained for drogued surface drifters from February 1979 through August 2000. These data were daily-averaged and then analyzed on a 0.5° latitude by 2.5° longitude grid. At each grid point data within ellipses of area $\pi \times (400\ \mathrm{km})^2$, oriented and scaled by the local variance, were fit with a function including a 2nd-order spatial polynomial, an annual harmonic, and a linear regression on the southern oscillation index. The ellipses were zonally elongated near the equator, and more spherical in the subtropics. Grid points with less than 25 drifter days per $(1^{\circ})^2$ in their ellipse were not used. With one exception, only the means from these fits are analyzed here.

Data density from 1990–2000 is about six times higher than that from 1979–1989. In addition, the drifters have varying spatial coverage (Figure 1). This uneven coverage is partly due to heavy drifter deployment in locations such as the California Current. Also, drifters quickly exit areas of surface divergence, such as the equator, and gather in areas of surface convergence. The mean velocity field is doubtless influenced by drifter distributions. For instance, drifters only linger near the equator during El Niño with its anomalously weak trades and northerly winds in the east.

3. Surface velocity

The mean surface drifter velocity field (Figure 1) is quite similar to one constructed using less data but a more sophisticated mapping with longer zonal length scales [*Reverdin et al.*, 1994]. The geostrophic currents are predominantly zonal. They are westward, except for the North Equatorial Countercurrent (NECC) and the weaker SECC. These currents mostly extend to the base of the thermocline.

The bulk of the Pacific STC upwelling limb occurs on the equator, with only small contributions from coastal and other upwelling. Thus, most of the STC surface limb should flow poleward from the equator. The mean velocity field (Figure 1) clearly reflects the poleward component of Ekman drift, linked to the upwelling and driven by the easterly trade winds. While surface drifters measure velocity at 15 m, shipboard ADCP data suggest that the influence of poleward Ekman flow extends below that depth and even the mixed layer [*Wijffels et al.*, 1994].

4. Surface divergence

Like the surface velocity field, the tropical surface divergence field has short meridional and long zonal scales. Equa-

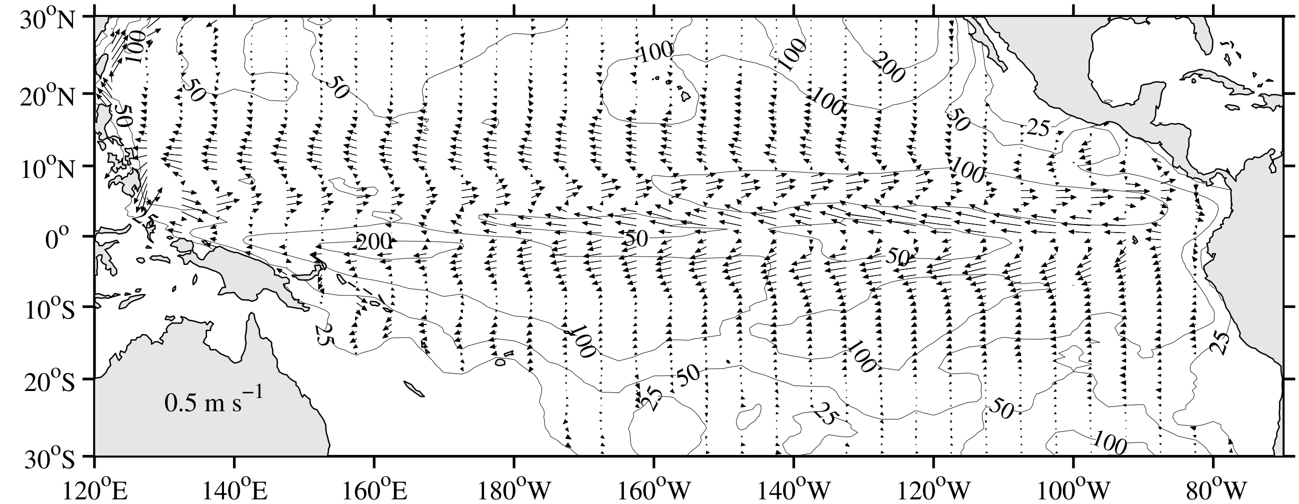

Figure 1. Mean surface velocity vectors. Velocity scale is shown over Australia. Drifter days per $(1°)^2$ in fitting ellipses are contoured at doubling intervals starting from 25, the minimum for use in analyses.

torial Pacific surface divergence computed from drifter data [*Poulain*, 1993] is localized about the equator, to meridional scales of tens of kilometers. Here the divergence is estimated from centered differences of the gridded mean velocity, which smooths over larger meridional scales. Maximum values are in the central equatorial Pacific, 1×10^{-6} s^{-1} near 140°W. A clear pattern of equatorial divergence flanked by off-equatorial convergence persists from 165°E to 85°W (not shown). This pattern is reflected in the zonal average over this longitude range (Figure 2). The meridional component of the divergence dominates the zonal term near the equator, and interior divergence is small poleward of ±8° latitude.

A characteristic tropical Pacific surface layer depth is 30 m [*Ralph and Niiler*, 1999; *Lagerloef et al.*, 1999]. Applying the zonally averaged divergence estimate over 30 m then meridionally integrating gives upwelling of 50×10^6 m^3 s^{-1} within ±2° latitude between 165°E and 85°W. This value is in rough agreement with prior direct estimates [*Johnson et al.*, 2001], but the drifter data suggest much closer equatorial confinement.

The off-equatorial downwelling within ±8° latitude is evidence of the shallow tropical cells present in models both simple [*Lu et al.*, 1998] and complex [*Kessler et al.*, 1998]. In models these cells are shallow, near-equatorial phenomena that are superimposed on the STC, and the downwelling water hardly reaches the thermocline. Meridional integration of the zonally averaged divergence estimate suggests that roughly half the water that upwells on the equator downwells again before it reaches ±8°, recirculating near the equator.

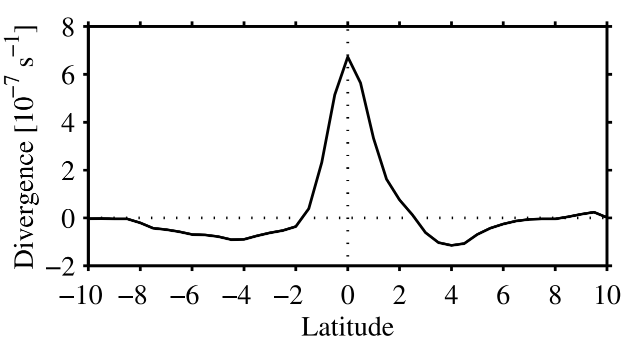

Figure 2. Mean surface divergence zonally averaged from 165°E to 85°W.

5. Surface pathways and time scales

Two different analyses of the drifter data shed light on time scales and pathways of the Pacific STC surface limb. In both cases pathways are studied starting from ±0.75° latitude between 165°E and 85°W, where surface divergence suggests strong equatorial upwelling. One analysis uses streamlines from the mean velocity field presented above. Another analysis uses the drifter data directly as described below.

Streamlines constructed from the mean velocity field starting from ±0.75° latitude (Figure 3) show generally poleward and westward flow in both hemispheres. The NECC interrupts the westward trend in the northern hemisphere, even diverting a few streamlines to the Central American Coast. The SECC has a similar, but much reduced, effect west of the dateline. After a half year the streamlines reach a median ±9° latitude, after a year they reach ±13°, and after 2 years ±22°; their poleward and westward tendency slows upon reaching the western subtropics.

An alternate analysis uses drifter trajectories that pass within ±0.75° latitude between 165°E and 85°W. This restriction limits the analysis to 283 drifters in the north and 347 in the south. The drifters from each hemisphere are binned in 10° longitude bins based on where they last cross ±0.75°. Ensemble drifter trajectories are computed for each bin as a function of time after they last cross ±0.75°, until less than nine drifters remain alive in the bin.

Like the mean streamlines, these trajectories (Figure 4) have generally poleward and westward flow in both hemispheres, with eastward interruptions in the SECC and NECC. Most of the trajectories last at least half a year, reaching a median ±9° latitude, similar to the mean streamlines. Less than a third of the trajectories last a year, but those that do reach ±13° at that time, also similar to the mean stream-

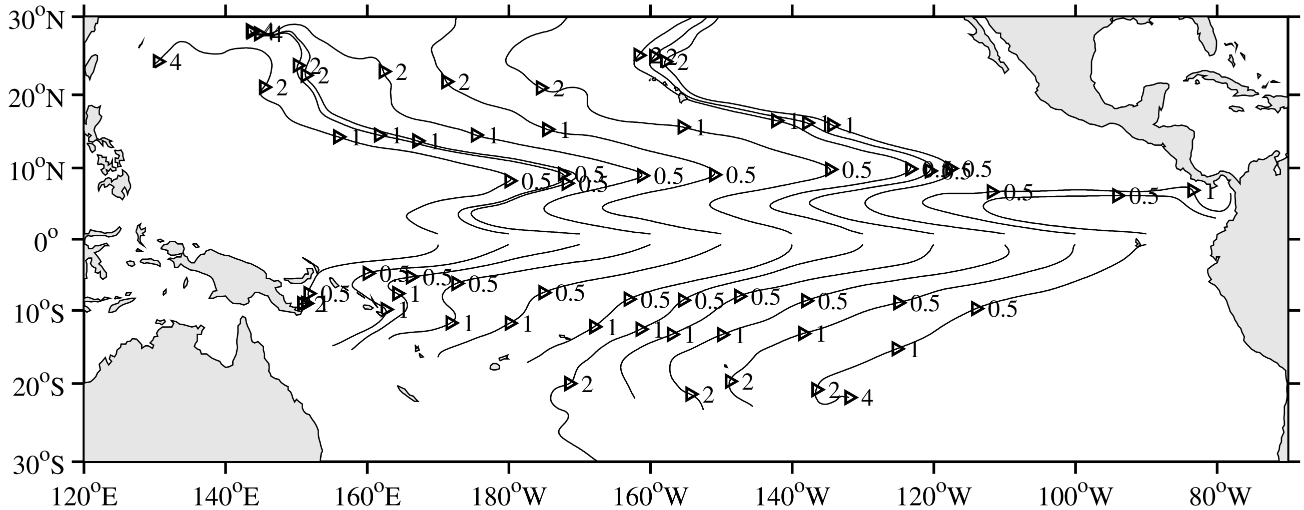

Figure 3. Mean streamlines starting at ±0.75° latitude between 170°E and 90°W (black lines) and followed for up to 4 years. Times in years at doubling intervals starting from 0.5 are right of triangles.

lines. None of the trajectories attain the subtropics because drifter lifetimes are too short.

Time scales for surface flows to reach the subtropics from the equator are shorter than the decadal ones for subsurface flows from the subtropics to reach the equator [*Fine et al.*, 1987]. However, half of the water upwelled at the equator may recycle through the shallow tropical cells, which likely increases the time scale of half a year for water to move from the equator to ±9° latitude.

The ensemble drifter trajectories are all headed for the western subtropics before they stop because of drifter deaths. The mean streamlines almost all do find the western subtropics in both hemispheres. In contrast, water that comprises the equatorial-flowing thermocline STC limb is subducted in the eastern half of the subtropics [*Gu and Philander*, 1997; *Johnson and McPhaden*, 1999]. This difference between subduction regions from which water in the STC proceeds to the equator and where that water reaches the subtropics after being upwelled supports model results that the STCs are not closed, but linked to the global ocean circulation [*Lu et al.*, 1998].

6. Discussion

The drifter data allow quantification of several aspects of the Pacific STC surface limb. The mean surface currents show the superposition of poleward Ekman drift and the zonal geostrophic currents. The mean divergence between 165°E and 85°W suggests upwelling of 50×10^6 m^3 s^{-1} across 30 m around the equator. Downwelling of half that magnitude within ±8° latitude gives evidence of recirculation in shallow tropical cells. Ensemble drifter trajectories suggest time scales of about half a year to reach ±9°, neglecting any delays due to shallow tropical cell recirculations. Mean streamlines take 2 years to reach ±22° and enter the subtropics in the west, far from the subduction regions that feed the equatorward flow of the STCs. This mismatch of entry and exit regions for the Pacific STC suggests that it is not closed, but part of the global circulation.

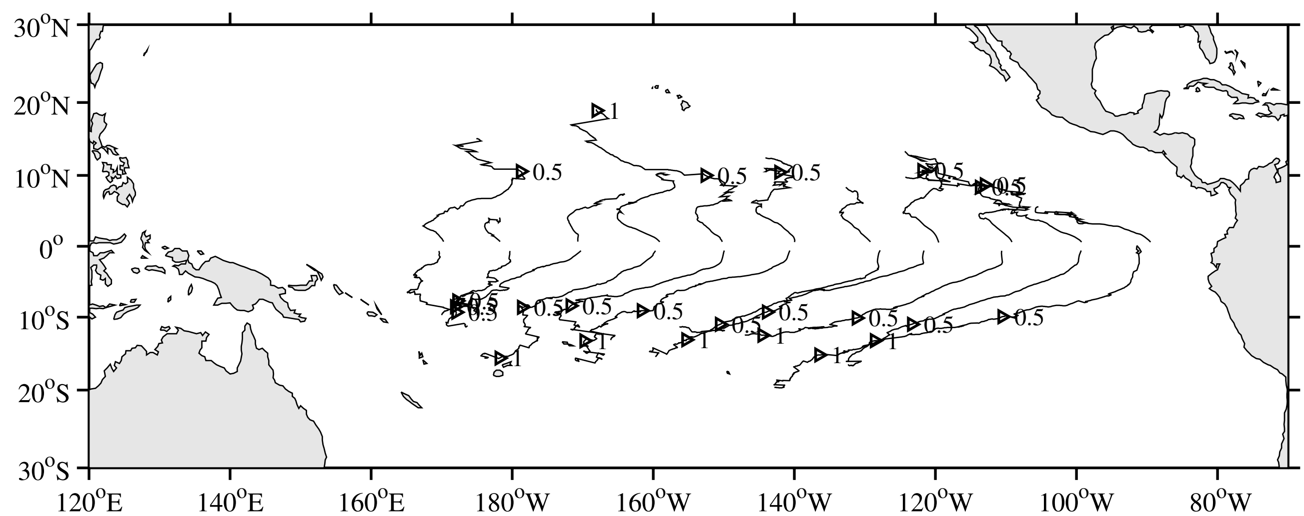

Figure 4. Ensemble drifter trajectories for 10° longitude bins between 165°E and 85°W starting at ±0.75° latitude. Trajectories (black lines) stop when less than nine drifters are alive. Time in years at doubling intervals starting from 0.5 are right of triangles.

The Indonesian throughflow links the Pacific STC to the global circulation. More thermocline water reaches the equator from the south than the north [*Johnson and McPhaden*, 1999; *Butt and Lindstrom*, 1994]. This water must modify its potential vorticity (PV) from negative to positive to reach the throughflow in the north. There are two likely routes. One is in the western boundary current, where lateral friction allows PV modification. However, while the water feeding the throughflow must ultimately come from the south, water properties suggest that it bears the imprint of North Pacific surface forcing [*Ffield and Gordon*, 1992]. If this water crosses the equator by upwelling to the sea surface, surface forcing can help change its PV and eventually impart the observed North Pacific water mass properties. However, hemispheric asymmetry in the surface transport is not evident in the drifter velocities, under the very large assumption of identical vertical structure for meridional velocities in both hemispheres. Determination of the dominant route requires knowledge of the vertical structure of near-surface flow.

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